Robert Fusaro and Fred Oswald of the Mechanical Components Branch discussed “Candidate Coatings and Dry Traction Drives for Planetary Vehicles”. Vehicles to be designed for exploration of planets and moons of the solar system will require reliable mechanical drives to operate efficiently. Long-term operation of these drives will be challenging because of extreme operating conditions. These extreme conditions include: very high and/or very cold temperatures, wide temperature ranges, dust, vacuum or low-pressure atmospheres, and corrosive environments.

Most drives used on Earth involve oil-lubricated gears. However, due to the extreme conditions on planetary surfaces, it may not be advisable or even possible to use oil lubrication. Unfortunately, solid lubricants do not work well when applied to gears because of the high contact stress conditions and large sliding motion between the teeth, which cause wear and limit life. We believe traction drives will provide an attractive alternative to gear drives. Traction drives are composed of rollers that provide geometry more conducive to solid lubrication. Minimal slip occurs in this contact geometry and thus there is very low wear to the solid lubricant.

The challenge for these solid-lubricated drives is finding materials or coatings that provide the required long-life while also providing high traction. We seek materials that provide low wear with high friction.
Potential Solid Lubricants for Traction Drives

Robert L Fusaro
Retired
NASA-Glenn Research Center
Cleveland, Ohio

What is a Solid Lubricant

General Definition
A solid material which, when interposed between two relatively moving surfaces reduces the friction and wear
Why Use a Solid Lubricant?

1. **Used where fluids are not suitable**
   - Where liquids would contaminate
   - At high temperatures (fluids decompose)
   - At low temperatures (fluids freeze)
   - Chemical reactive environments
     - Liquid oxygen or hydrogen
     - Liquid fluorine
     - Molten alkali metals

2. **Used for mechanical design advantages**
   - Dynamic stability can be improved
     - Solid lubricated air bearings
   - Placing bearings closer to heat sources, allowing the use of shorter shafts
   - Simple, lightweight design
     - No cooling required
     - Eliminate pumps, heat exchangers and recirculating oil systems
     - Number of seals can be reduced

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**Classes of Solid Lubricants**

<table>
<thead>
<tr>
<th><strong>Soft Metals</strong></th>
<th><strong>Polymers</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>PTFE</td>
</tr>
<tr>
<td>Silver</td>
<td>Polymides</td>
</tr>
<tr>
<td>Lead</td>
<td>UHMWPE</td>
</tr>
<tr>
<td>Indium</td>
<td>PEEK</td>
</tr>
<tr>
<td>Barium</td>
<td>Polyacetal</td>
</tr>
<tr>
<td></td>
<td>Phenolic Resins</td>
</tr>
<tr>
<td></td>
<td>Epoxy Resins</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Lamellar Solids</strong></th>
<th><strong>Other Materials</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>Fluorides of Ca, Li, Ba</td>
</tr>
<tr>
<td>Molybdenum Disulfide</td>
<td>Rare Earths</td>
</tr>
<tr>
<td>Intercalated Graphite</td>
<td>Sulfides of Bi, Cd</td>
</tr>
<tr>
<td>Fluorinated Graphite</td>
<td>Oxides of Pb, Cd, Co, Zn</td>
</tr>
<tr>
<td>Cadmium Iodide</td>
<td>Diamond Coatings</td>
</tr>
<tr>
<td>Lead Iodide</td>
<td></td>
</tr>
<tr>
<td>Molybdenum Diselenide</td>
<td>Diamond Like coatings</td>
</tr>
<tr>
<td>Phthalocyanine</td>
<td></td>
</tr>
</tbody>
</table>
Methods of Employing Solid Lubricants

1. Coatings/Films
   a. Rub or Burnish
   b. Incorporate into a Binder System
      i. Sodium Silicate
      ii. Phenolic Polymer
      ii. Polyimide Polymer
   c. Vacuum Deposition Techniques
   d. Plasma Spraying
   e. Powder detonation

2. Solid Bodies/Composites
   a. Particulate
   b. Fiber Reinforced

3. Oil Dispersions/Greases

4. Powder Lubrication

Factors which Affect Solid Lubricant Performance

- Type of substrate material to which a film is deposited
- Surface finish of the substrate material
- Type of counterface material
- Surface topography of the counterface
- Hardness of substrate material
- Hardness of counterface material
- Surface or surfaces to which a solid lubricant is applied
- Geometry of sliding specimens
- Contact stress or pressure
- Temperature
- Sliding Speed
- Environment
- Atmosphere
- Fluids, Dirt or Dust
A coating that has structural strength but still has the ability to flow at the interface can support the load and the wear process is one of gradual wear through the coating (left). Coatings without sufficient structural strength can still lubricate by forming a very thin film at the metallic surface. The life of this lubrication mechanism is strongly dependent on the topography of the metallic surface.

Photomicrograph showing the thin film lubricating mechanism for a polyimide coating that was unable to support the load. A thin film of material at the metallic surface has formed and the roughness (scratches) in the surface helps hold the material in place to provide a long endurance life. Most soft lamellar solid lubricants lubricate by this mechanism. Proper substrate surface preparation is important for obtaining a long endurance life.
### Friction and Wear of Sliding Couples

(Experimental Conditions: 50% RH Air, 25 C, 10 N load)

<table>
<thead>
<tr>
<th>Disk Lubricant Material</th>
<th>Film or Solid</th>
<th>Pin Material</th>
<th>Friction Coeff.</th>
<th>Disk Wear Rate (mm²/Nm x 10⁻⁶)</th>
<th>Pin Wear Rate (mm²/Nm x 10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyphenylene Sulfide Composite</td>
<td>Solid</td>
<td>440 C</td>
<td>0.30</td>
<td>6200</td>
<td>0</td>
</tr>
<tr>
<td>Polyimide (PI-4701)</td>
<td>Film</td>
<td>440 C</td>
<td>0.13</td>
<td>4000</td>
<td>0</td>
</tr>
<tr>
<td>Polyamide-imide Composite</td>
<td>Solid</td>
<td>440 C</td>
<td>0.37</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>Polyimide/Graphite Powder Composite</td>
<td>Solid</td>
<td>440 C</td>
<td>0.37</td>
<td>900</td>
<td>0</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>Solid</td>
<td>440 C</td>
<td>0.18</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Polyimide/Graphite Fiber Composite</td>
<td>Solid</td>
<td>440 C</td>
<td>0.19</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>Sputtered MoS₂</td>
<td>Film</td>
<td>440 C</td>
<td>0.65</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Sputtered MoS₂</td>
<td>Film</td>
<td>440 C</td>
<td>0.87</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Polyimide (1000 C)</td>
<td>Film</td>
<td>440 C</td>
<td>0.62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diamond-like Carbon</td>
<td>Film</td>
<td>440 C</td>
<td>0.85</td>
<td>800</td>
<td>0.02</td>
</tr>
<tr>
<td>PS-200</td>
<td>Film</td>
<td>Cobalt Alloy</td>
<td>0.20</td>
<td>2100</td>
<td>3000</td>
</tr>
</tbody>
</table>

This table shows the friction and wear of various sliding couples illustrating that low friction and low wear do not always occur at the same time. For traction drives we want high friction and low wear. One should not assume that just because you have high friction you will also have high wear.

### Friction and Wear of Composite Materials

(Testing Conditions: Pin-on-Disk. 200 rpm, 1 kg load, Dry Air, 25oC)

<table>
<thead>
<tr>
<th>Type of Solid Lubricant Composite</th>
<th>Counterface</th>
<th>Fric. Coeff.</th>
<th>Composite Wear Rate (m²/Nm x 10⁻⁵)</th>
<th>Test Duration (kc)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRPI</td>
<td>Al₂O₃</td>
<td>0.42</td>
<td>1</td>
<td>1143</td>
<td></td>
</tr>
<tr>
<td>GFRPI</td>
<td>Si₃N₄</td>
<td>0.41</td>
<td>3</td>
<td>2393</td>
<td></td>
</tr>
<tr>
<td>Vespol Polyimide SP-21</td>
<td>440 C</td>
<td>0.43</td>
<td>3</td>
<td>2244</td>
<td></td>
</tr>
<tr>
<td>GFRPI</td>
<td>440 C</td>
<td>0.12</td>
<td>24</td>
<td>1540</td>
<td></td>
</tr>
<tr>
<td>Vespol Polyimide SP-1</td>
<td>440 C</td>
<td>0.35</td>
<td>31</td>
<td>2195</td>
<td></td>
</tr>
<tr>
<td>Vespol Polyimide SP-3</td>
<td>440 C</td>
<td>0.40</td>
<td>61</td>
<td>1183</td>
<td></td>
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<tr>
<td>Torlon</td>
<td>440 C</td>
<td>0.35</td>
<td>157</td>
<td>1034</td>
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<tr>
<td>Vespol Polyimide SP-3</td>
<td>Si₃N₄</td>
<td>0.35</td>
<td>---</td>
<td>157</td>
<td>Ball Crazed</td>
</tr>
<tr>
<td>Vespol Polyimide SP-1</td>
<td>Si₃N₄</td>
<td>0.35</td>
<td>---</td>
<td>25</td>
<td>Ball Crazed</td>
</tr>
</tbody>
</table>

This table shows the friction and wear of some commercially available composite materials sliding against various counterface materials in dry air. The table illustrates how the counterface can markedly affect the tribological properties of a composite. Thus it may be possible to develop better traction drive rollers by considering materials that have higher friction when sliding against low wear composites or coatings.
This table compares the friction and wear properties in air and vacuum to illustrate how oxygen and water vapor can affect tribological properties. The results show that the PMDA polyimide or the Graphite Fiber Reinforce Polyimide (GFRPI) have potential for traction drive rollers in a planetary environment.

Plasma Sprayed (PS) coatings were developed for high temperature lubrication applications. This figure illustrates that in oscillating journal bearing tests the friction remains relatively high over a range of temperatures from -107°C to +870°C. This high friction characteristic makes these materials candidates for traction drives for space applications on cold planetary surfaces.
The loss in radial clearance (wear) for the oscillating journal bearing tests indicates that wear is relatively low at -107°C when compared to room temperature (25°C) indicating that for cold planetary surfaces this could be a good traction drive material.

**Final Remarks**

**Solid Lubricated Traction Drives**

- Desire Solid Bodies or Coatings that have low wear and have the ability to support the loads.
- Desire Solid Lubricants that have relatively high friction coefficients.
- Plasma Sprayed (PS-101) Coatings have been tested at low temperatures and seem to have desirable characteristics.
- Certain types of polyimides used as coatings and fiber reinforced polyimide composites are also possible candidates for this application.
**Investigating Dry Traction for Planetary Vehicle Drives**

Fred Oswald  
NASA Glenn Research Center

![Image of Mars Athena '03 rover and Boeing concept for a pressurized Lunar rover.](image)

Left, Mars Athena '03 rover. Right, Boeing concept for a pressurized Lunar rover.

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**Objective**

- Develop solid lubricated traction drive for rover vehicles exploring planetary surfaces
- Provide efficiency & long life in hostile environments

**Benefits**

- Higher mechanical efficiency than existing drives
- Provide longer life with high reliability
- Allow operation below ~-60° C
- Provide robustness to harsh environment
- Minimize weight to save launch cost
Wear Resistant Solid Lubricants

Friction Coefficient vs Wear Rate for 10 Polymers in 10^-3 Torr Vacuum

Polymer Materials
1. Polyphenylene sulfide w/50% graphite fibers
2. Poly(amic acid)/imide/PTFE and graphite (Torlon)
3. Polyimide (Vespel)
4. PEEK/graphite (Torlon)
5. 100% PMDA polyimide
6. 90% PMDA//20% PTFE polyimide
7. Graphite fiber-reinforced polyimide
8. 100% PMDA polyimide film
9. PTFE polyimide film
10. PTFE polyimide 90% CEx additive film

For a traction drive, we need high friction (traction) with low wear. The 100% PMDA polyimide solid (#5) and film (#8) materials show promise.

Proof of Concept Traction Tester

This simple device can test traction roller materials in vacuum. It includes provision to cool the rollers through hollow shafts. With minor modification, it can also test gears.
Detail of Rollers, Shafts & Bearings

Proof of Concept Traction Tester
Roller unit shown with vacuum cube

Partly completed traction drive tester is at left. Project awaits restored funding.